Assessing the ecological soundness of organic and conventional agriculture by means of life cycle assessment (LCA) – a case study of leek production

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ABSTRACT

Purpose:
Sustainable agriculture implies the ability of agro-ecosystems to remain productive in the long-term. It is not easy to point out unambiguously whether or not current production systems meet this sustainability demand. A priori thinking would suggest that organic crops are environmentally favourable, but may ignore the effect of reduced productivity which shifts the potential impact to other parts of the food provision system. The purpose of this paper is to assess the ecological sustainability of conventional and organic leek production by means of life cycle assessment (LCA).

Design/methodology/approach: A cradle-to-farm gate LCA is applied, based on real farm data from two research centres. For a consistent comparison, two functional units (FU) were defined: 1 ha and 1 kg of leek production.

Findings: Assessed on area basis, organic farming shows a more favourable environmental profile. These overall benefits are strongly reduced when the lower yields are taken into account. Related to organic farming it is therefore important that solutions are found to substantially increase the yields without increasing the environmental burden. Related to conventional farming, important potential for environmental improvements are in optimising the farm nutrient flows, reducing pesticide use and increasing its self-supporting capacity.

Research limitations/implications: Our research is a cradle-to-farm gate LCA, future research can be expanded to comprise all phases from cradle-to-grave to get an idea of the total sustainability of our present food consumption patterns. Our research is also limited to the case of leek production. Future research can apply the methodology to other crops.

Originality/value: To date, there is still lack of clear evidence of the added value of organic farming compared to conventional farming on environmental basis. Few studies have compared organic and conventional food production by means of LCA.

Keywords: Life cycle assessment (LCA), organic farming, conventional farming, ecological sustainability, environmental impact
Paper type: Case study

INTRODUCTION

Sustainable agriculture implies the ability of agro-ecosystems to remain productive in the long-term, i.e. to be economically competitive, to produce high quality food in sufficient quantities at affordable prices, and to be environmental benign (UN-DSD, 2000). Herdt and Steiner (1995) point out that it is hard to know whether current agro-ecosystems are sustainable in the sense of remaining productive in the long run, as the continuous increase in human-made inputs applied in most agro-ecosystems has increased yields but may be offset by reductions in the quality of the natural capital (e.g. land degradation, pollution, depletion of natural resources) and thus of the underlying productive capacity (Kramer *et al.*, 1999; van der Werf and Petit, 2002; Nonhebel, 2004).

Consumers, agencies, farmers and decision makers from the agri-food sector have become increasingly aware of the environmental impacts related to agricultural production and the fact that our present food consumption patterns are far from sustainable (Öborn *et al.*, 2002). In addition, the increase of environmental pressure from agriculture is unlikely to reverse in the near future, since the world population continues to increase, diets continue to shift towards animal products and energy consumption in food production continues to intensify as a result of industrialization (Goodland, 1997; Tukker *et al.*, 2005; FAO, 2008; Schau and Fet, 2008).

During the last decade, organic farming has become a significant element in policies promoting food safety and environmental quality of food production in Europe as it rules out the use of mineral fertilizers and other chemicals such as pesticides. Organic farming has, nevertheless, developed with little input from scientific research institutions (Lampkin *et al.*, 1999). Therefore, the development and characteristics of organic technology raise important research questions concerning its productivity and technical efficiency in using capital, labour and natural resources such as land and energy (Lampkin *et al.*, 1999).

There is a growing awareness that a single-issue approach to an environmental problem may not lead to an effective long-term strategy and that efficient methods to comprehend and assess agricultural impacts on the environment by combining suitable indicators are very much needed. Furthermore, besides impacts resulting from on-farm activities, agriculture also causes environmental pressure indirectly through the usage of goods and services for farm operations. The provision of these goods and services entails resource use and pollutant emissions in industries 'upstream' of agriculture, such as the power, chemical and steel industries. These resources and pollutants should also be considered when assessing the sustainability of agriculture. This understanding has triggered the adaptation of various holistic methods for the evaluation of the environmental impact of agriculture, e.g. ecological footprint analysis and life cycle assessment (LCA). Such methods take into account a number of environmental issues of concern as it does not make any sense at all to improve one part of the system, if this 'improvement' has negative consequences for other parts of the system which may outweigh the advantages achieved.

Life cycle assessment (LCA) has proven to be a valuable tool to address questions on the environmental impact of various agriculture production systems, relating to both the identification of the subsystems that contribute most to the total environmental impact and the comparison of products and processes with the same function (e.g. Haas *et al.*, 2000; Brentrup *et al.*, 2001; Cederberg, 2002; Brentrup *et al.*, 2004; Stern *et al.*, 2005; Charles *et al.*, 2006; Milà i Canals *et al.*, 2006; Thomassen *et al.*, 2008). Cederberg and Mattsson (2000), Haas *et al.* (2001), de Boer (2003), 's Gravendijk (2006) and Thomassen *et al.* (2008) adopted the LCA technique to gain insight in conventional and organic milk production chains. Nienhuis en de Vreede (1994b), Kramer *et al.* (2000), van Woerden (2001) and Halberg *et al.* (2006)

assessed the LCA profile of organic and conventional vegetables. Nicoletti *et al.* (2001) applied LCA to investigate the environmental performance of organic and conventional vine growing, and Stern *et al.* (2005) studied various future scenario's for sustainable pig production with LCA. None of those comparative studies considered the effects of pesticides, because of methodological issues, although a main benefit from organic production is that no pesticides are used. Within the scope of this study, emphasis will therefore be put on the environmental impacts resulting from pesticide use.
This paper aims at assessing the ecological sustainability of conventional and organic leek growing by means of LCA. This case study is based on real farm data provided by two research centres. Focus is on leek production, because this is one of the most important field-grown vegetables in Flanders (Belgium) both for organic and conventional crops.

MATERIAL AND METHODS

Life cycle assessment (LCA) has been defined as a process to evaluate the environmental burdens associated with a product, process or activity by identifying and quantifying energy and materials used and wastes released into the environment; to assess the impact of the energy and materials used and released into the environment; and to identify and evaluate opportunities for environmental improvements (Consoli *et al.*, 1993). According to the methodological framework established by the International Organization for Standardization (ISO, 1997) LCA consists of four phases:

1) Goal and scope definition, in which the intended application as well as the extent of the study has to be clearly exposed;
2) Inventory analysis (LCI), where information about the product system is gathered and relevant inputs and outputs are quantified;
3) Impact assessment (LCIA), which converts the flows from the inventory into indicators related to the potential associated impacts;
4) Interpretation, where the findings of the two previous steps are combined and evaluated to meet the previously defined goals of the study.

More information on the LCA methodology can be found in Heijungs *et al.* (1992a; 1992b), Consoli *et al.*(1993), Lindfors *et al.* (1995), van den Berg *et al.* (1995), Guinée *et al.* (2001), Baumann and Tillman (2002) and Rebitzer *et al.* (2004).

LCA was initially developed to evaluate industrial products and processes. Since agricultural systems are sufficiently different from industrial systems, applying LCA to agricultural systems without due consideration of the specific characteristics of agriculture may give rise to problems. In the past, several studies have been performed to identify these bottlenecks and to investigate the extent to which the LCA method is suitable for use in the agricultural context (Andersson *et al.*, 1994; Nienhuis and de Vreede, 1994a; Weidema *et al.*, 1995; Wegener Sleeswijk *et al.*, 1996; van Zeijts and Reus, 1996; Meeusen-van Onna and Leneman, 1996; Sengers and Meeusen-van Onna, 1996; Audsley *et al.*, 1997; Diepenbrock *et al.*, 1997; Andersson, 1998; Cowell, 1998; Mattsson, 1999; Rossier, 1999; Andersson, 2000; Haas *et al.*, 2000; Brentrup *et al.*, 2001; Van Koppen and Meeusen, 2001; Brentrup, 2003; Mattsson and Sonesson, 2003; Brentrup *et al.*, 2004). During the last decade, the progress in the development of LCA in the agri-food sector in terms of methodological robustness and data availability has also been subject of a series of conferences and seminars (Weidema, 1993; Ceuterick, 1996, 1998; Weidema and Meeusen, 2000a, 2000b; Geerken, 2001; Halberg, 2004; Jensen *et al.*, 2005; Guinée *et al.*, 2006; SIK, 2007).

Goal and scope definition

The goal and scope definition is the phase in which the initial choices which determine the entire working plan are made (Guinée *et al.*, 2001). The aim of this case study is to compare the environmental impact resulting from organic and conventional leek production, to identify the parameters which have the largest environmental impact in the systems studied (hot-spots) and to propose potential improvement options for both systems.

Functional unit

To enable comparison, a reference unit, to which all the environmental impacts are related, has to be defined. According to the LCA terminology this reference unit is called a functional unit (FU) (ISO, 97). As agricultural systems are naturally multi-functional, the definition of a FU is not always a straightforward procedure and can substantially affect the outcome of the study (Haas *et al.*, 2000). This issue has been discussed by various authors (amongst others Wegener Sleeswijk *et al.*, 1996; Haas *et al.*, 2000; Schau and Fet, 2008). According to Cowell (1998) the function of agriculture can be related both to the landscape value, an external value, and to the production of products, which functional value is reflected in the product price. An important question in this respect is whether to express the FU on a mass or area basis. According to Haas *et al.* (2000) a mass based FU should solely be used if a reasonable cause exists and if allocation problems are satisfactorily solved in order to correctly link the impacts with the correct subsystem and related product. They state will rarely be the case. They provide an interesting example on how the FU definition affects the LCA-results in a LCA study of 18 grassland dairy farms covering three farming intensity levels, using four different FU definitions, namely whole farm, farmed area (ha), livestock unit (each 500 kg live-weight of cattle) and product unit (tonne of milk). Haas *et al.* (2000) state that within the biodiversity, landscape image and animal husbandry categories the whole farm is the only meaningful unit. Only abiotic categories can also be related to the livestock unit or the product unit, but different figures may result depending on the FU chosen. In a case study on optimisation fertilizer intensity for wheat production systems, Charles *et al.* (2006) consider three functions of agriculture and three different related FUs, being landscape upkeep (FU=1 ha), production (FU=1 tonne of grain) and production with quality requirements (FU=1 tonne of grain with constant quality). Depending on the FU considered different results were obtained. On the one hand, the assessment per ha clearly showed that if the main objective is landscape upkeep, the fertilization intensity should be reduced to a minimum. In that case, alternative crops should also be considered to ensure this objective with minimal pollution. On the other hand, if the main objective is a certain amount of wheat production (of a defined quality), the assessment showed that intensification of fertilisation has lower impacts if high yield and quality are guaranteed by an adequate corresponding fertilizer rate. Therefore, Charles *et al.* (2006) consider multiple possibilities of assessment as potentially complementary with respect to the multi-functional role of agricultural activity. In their view, these different FUs each highlight another aspect of the production process.
Obviously, these considerations are also important when comparing systems with different levels of productivity per ha, such as conventional and organic farming. Therefore, two different FUs are defined in our study. Firstly, the environmental impact of 1 kg of organically or conventionally grown leek produced is assessed. This definition reflects its function as a producer of market goods. Secondly, an assessment is performed, with the FU defined as 1 m² of organic or conventional leek, which is certainly a relevant FU when considering the environmental impact on a local area, which is an important issue within the organic philosophy and corresponds to the function of agriculture as a producer of non-market goods (e.g. environmental services).

System boundaries

System boundaries are chosen preferably reflecting the boundary between the natural and the technical systems under study. The choice of system boundaries, however, is always debatable, particularly with food production, where the inclusion of biological processes renders the distinction between technological systems and nature unclear (Berlin and Uhlin 2004; Berlin, 2002; Schau and Fet, 2008). When analysing the emissions related to the agricultural sector one would ideally aim at a full LCA approach (i.e. from cradle-to-grave).
However very few food studies have attempted to include the entire life cycle; the subsystems most often omitted are the consumer and waste handling phases (Andersson, 2000; Schau and Fet, 2008). In our study we decided to truncate the system boundaries at farm level (cradle-to-farm gate). There are three reasons for this: first, comparing differences in the transport and marketing processes downstream from the farm gate is a complex study in itself. Second, the downstream farm gate organic market is still evolving importantly and optimising itself, implying that results from such a study may be soon outdated. Third the few studies that have attempted a full LCA (e.g. Andersson *et al.*, 1998; Jungbluth *et al.*, 2000; Berlin, 2002; Mattsson and Wallén, 2003; Ziegler *et al.*, 2003; Thrane, 2006) have shown in general that the direct environmental impact of consumption and waste handling phases were of minor importance relative to the production phase, i.e. the agricultural activity. Based on these insights it was decided to omit all post-harvest activities such as transport, processing, cooling and retailing, and to exclude the consumption (e.g. washing and cooking at home) and waste management phase from the scope of the present work.
Yet, in this context supply chain studies on the Belgian (organic) food sector, find that important extra costs per kg end-product are incurred downstream from the farm gate for organic products relative to conventional products, mainly due to the relative very small scale of the organic food sector up to today (Ameloot et al, 2003; Aertsens et al, 2008). The studies indicate especially higher costs for transport due to the smaller volumes and suboptimal organisation, higher fall out of organic vegetables due to a lower turnover and the higher transaction costs when organising the supply. As the organic sector is still scaling up and getting better organised, we believe that these extra costs will be further reduced in the future.

In addition to the farmer's on-field activities, the emission of relevant up-stream activities (indirect emissions) such as the production and processing of mineral fertilizers and pesticides were also taken into account. Buildings and machinery were excluded because of the similarity in buildings between the different farm types. Moreover, building infrastructure is more important for animal farming than crop production (Nemecek and Erzinger, 2005). Machinery was excluded since there is a lack of data on machinery used in crop production.

Inventory analysis

The Life Cycle Inventory (LCI) consists of the compilation and quantification of relevant inputs and outputs associated with the activities within the system boundaries and related to the production of the FU, including the use of resources and emissions to air, water and soil. In this LCA study, like in many, data relating to specific agricultural inputs, consumption and agricultural practices, so-called on-farm emissions or foreground data, are obtained directly from farmers (e.g. by means of questionnaires, surveys, logbooks, data from agricultural extension services). Data on environmental interventions associated with the operations in the background system, off-farm emissions or background data (agro-chemicals production, fertilizer production, machinery production, delivery of energy carriers and transportation), are mostly taken from literature or databases of different kinds, being common data sources for LCA-practitioners.

Background data

Data on background processes were mainly obtained from literature. As mineral fertilizers are not allowed in organic farming systems, farmyard manure alone is applied in this case. The LCA accounts the emissions and processes related to the transport of the manure to the organic farm and the manure spreading, but not those related to the production and storage of manure, as these are fully allocated to the corresponding animal products and breeding system. In conventional leek production ammonium nitrate (AN) is generally used as mineral nitrogen fertilizer. The data relating the AN production process were derived from Davis and Haglund (1999). Data on the energy use of the potassium fertilizer production are mentioned in Bϕckmann *et al.* (1990).

The energy required for the synthesis of active ingredients of pesticides is retrieved from Gaillard *et al.* (1997) based on energy balances published by Green (1987). These inventories were defined for active ingredients but not for commercial products, on the one hand, because of the large variety of commercial products, on the other hand, because the synthesis of the active ingredients is, in general, much more important than the formulation of the final product (Nemecek and Erzinger, 2005).

Fuel use related to the different agricultural operations is obtained from KTBL (2005).

Data relating to other background processes such as emissions due to transportation, energy production and energy use were retrieved from the databases included in the LCA software package SimaPro 7.1 which was used to perform this study.

Foreground data

In this section we discuss the processes related to the production of leek and focus on similarities and differences between the conventional and organic production system. The whole production process can be divided in several subprocesses, which are also summarized in Table 1 below: (1) raise plantlets from seed and harvest them; (2) soil preparation operations; (3) planting the leek plantlets; (4) weeding; (5) additional fertilisation processes; (6) applying crop protection and (7) harvesting. Specific data relating these on-farm processes for organic as well as conventional farming were obtained from two research centres, the Interprovincial Research Centre for Organic Farming (PCBT; pers. comm. Lieven Delanote) and the Provincial Research and Advisory Centre for Agriculture and Horticulture (POVLT: pers. comm. Danny Callens) respectively. The data obtained from these research centres can be considered representative in order to compare both farming systems as both centres are situated in the same region (Rumbeke-Beitem, Flanders) and are thus subject to analogue pedological and meteorological conditions. The data provided are average production data and or not based on data collection from a single year.

Table 1: Overview of activities for the conventional and organic production of leek (1 ha)

ACTIVITY	CONVENTIONAL	ORGANIC
SEEDBED		
1A. raise plantlets from seed;	- ploughing and soil preparation - sowing in an unheated plastic greenhouse: 1000 seeds/m², - applying crop protection (cf. Appendix A and B)	- ploughing and soil preparation - making of a false seedbed + weeding manually with a roller-type hoe before sowing - sowing on 5 cm of compost in an unheated plastic greenhouse: 1000 seeds/m², - no or limited crop protection (after sowing)
1B.harvesting plantlets	Time : 15 hours (mechanically)	Idem: Time : 15 hours (mechanically)
ARABLE LAND		
2A. working the green manure into the ground	Time: 3 hours with a rotary cultivator - 120 hp	Idem: Time: 3 hours with a rotary cultivator - 120 hp

2B. Soil cultivating	Time: 1,5 hour - 120 hp	Idem: Time: 1,5 hour - 120 hp
2C. Fertilisation/ Applying manure	- applying lime; e.g. marly lime - 800 kg potash magnesia sulphate - 25 ton farmyard manure - applying additionally 75 kg N from organic fertilizer - spraying Mg-sulphate: 1 to 3 times	- applying lime from a natural source; e.g. Ca-carbonate (Magkal/Vitacal,…) - 1000 kg Haspargit - 30 ton farmyard manure - applying additionally 75 kg N form an organic fertilizer
2D. working the manure into the soil	1,5 h 120 hp	Idem: 1,5 h 120 hp
2E. Ploughing	2 h ploughing with 3 shares (100 hp)	Idem: 2 h ploughing with 3 shares (100 hp)
2F. Rotary harrowing	3 h 120 hp	Idem: 3 h 120 hp
3. Planting	without ridges: 24 hours	Idem: without ridges (24 hours) 150 000 plants/ha = 200 000 seeds/ ha
4. Weeding	2 times earthing up	5 times, weeding and earthing up the leek 3 h/ha/time; tractor 50 to 70 hp
5. Additional fertilisation	Applying Ammonium Nitrate: up to 2 x 50 kg N; 0,5 h/ha, tractor 70 hp	
6. Crop protection	11 operations of spraying. For a detailed overview we refer to Appendix A and B.	2 treatments with Bacillus Thuringiensis (Xentari: 1 kg/ha) in August, against moth (Acrolepiopsis assectella)
7. Harvesting	- mechanically digging up: 80 hrs;120 hp - yield average: 37,5 ton/ha (Vandenberghe *et al.*; 2006);	- mechanically digging up: 80 hrs;120 hp - yield average: 27,5 ton/ha (PCBT);

Source: PCBT and POVLT Agriculture research centres (2007);

Concerning the LCA, the largest differences between the two farming systems are related to the spraying with synthetic crop protectors in the conventional production, which has not only consequences on the "ecotoxicity" of the production system as discussed later, but as it is performed 11 times throughout the production season this consumes 16,5 liter of diesel per hectare (cf. appendix A and B) and thus also results in a 6% higher total consumption of diesel for the conventional production in comparison with the organic leek production. The crop protection in the organic system consists of mechanical weeding and earthing up, which is performed 5 times during the production season and consumes in total 15,5 liter per ha (cf. appendix C). Another important difference between both farming systems are the yields which are on average 27% lower in the organic system. More details on the operations in both systems are given below.

(1) The cultivation of the young leek plants happens in the same way for the conventional and the organic production system, with one exception being the use of synthetic crop protection in the conventional system (cf. Appendix A and B).

(2) The soil preparation operations applied in the conventional and organic system are the same. They consist of (A) working the green manure into the ground with a rotary cultivator; (B) soil cultivation; (C) applying fertilisers, e.g. lime, Haspargit (C: 800 kg; O: 1000 kg), farmyard manure (C: 25 ton; O: 30 ton), organic fertilizer (C&O: 75kg N) and magnesium sulphate in the conventional system; working the fertiliser into the soil; (E) ploughing; (F) rotary harrowing. The quantities of fertiliser applied are somewhat different between the two farming systems.

(3) In our LCA for both the conventional and the organic leek production we study the system where leek is planted in a "flat field", i.e. not on ridges. For the organic system this is the predominant way leek is produced. For the conventional system, in Flanders about 50% of the leek is produced following this type of production and it may become more important in the future (pers. comm. Lieven Delanote). The planting activity for "flat field" production is the same in the conventional and organic system. The planting density, i.e. the number of leek plants per ha, is also the same.

(4) Concerning the earthing up and weeding activities, important differences exist between conventional and organic leek production. In the organic leek production system mechanical weeding is the main technique to suppress the negative impact of weeds. In the organic system the combined operation of earthing up and weeding is performed 5 times: a first time about 10 days after planting and then again every 10 to 14 days. In the conventional production, mechanical weeding is not important and the operation "earthing up" is only performed two times: a first time about 6 to 8 weeks after planting and a second time about 3 months after planting. The negative impact of weeds and pests in the conventional system is suppressed through the spraying of synthetic crop protectors (cf. below).

(5) In the conventional leek production ammonium nitrate is added to give some additional fertilisation to the young leek plants when they are planted. This synthetic fertiliser is not allowed in the organic leek production system.

(6) Concerning the protection of the leek plants against pests, in the conventional system 11 spraying operations are performed. The first operation about 4 weeks after planting and then every 2 weeks. A detailed overview of the applied crop protection products and their impact are presented in Appendix A and B. In the organic system, to protect the leek plants against leek moth (Acrolepiopsis assectella) two treatments with Bacillus Thuringiensis (Xentari: 1 kg/ha) are executed in August.

(7) Harvesting. The yields per ha for organic leek production are on average 27,5 ton per ha, while for the conventional system the average production is 37,5 ton per ha. This means that yields per ha are on average 27% lower in the organic system. The leek studied in both systems is harvested from October to December.

Field emissions related to fertilisation processes

Estimating field emissions in agricultural LCA's poses major problems as field emissions are highly variable and dependent on the actual situations (soil, climate, management). Nitrogen fertilizer emissions were assessed according to the different models mentioned in Brentrup *et al.* (2000; 2003). The mechanisms of nitrate leaching are influenced by soil properties and climate and, as a result, there may be considerable variation between the quantities of nitrate leached at different sites and in different years, even where nitrogen inputs are similar. As both research centres are situated in the same region, differences in the nitrogen are mainly due to differences in farming practices between conventional and organic systems. Table 2 gives an overview of the different models used to assess the nitrogen fertiliser emissions and the foreground data used to determine the overall nitrogen balances for both farming systems under study.

Growing crops require a considerable higher amount of nutrients than the quantity that is removed in the harvested parts, but much of this is recycled from (decaying) roots, leaves and other crop residues and from the soil itself. The residue from one crop may be more than

necessary for the following crop. As little is lost from the soil, the farmer applies P and K as necessary to maintain an adequate supply in the soil in the long-term. In this case study, following Audsley *et al.* (1997), it is assumed that any K surplus remains in the soil and an emission run-off factor of 0,024 kg P/kg P applied, is used. More detailed soil models and data could be used to model these flows more accurately (Cowell, 2000), but this level of detail is beyond the scope of our analysis. Detailed data on heavy metal contents in the fertilisers were not available, so they could not be included in the impact categories ecotoxicity and human toxicity.
When carrying out an LCA for a single agricultural product one should be aware that arable crops are usually grown in a crop rotation system, implying that all activities that may benefit more than one crop (e.g. fertilisation with phosphate, potassium and organic matter) should in an optimal situation be identified and allocated to the crops according to their uptake efficiency (van Zeijts *et al.*, 1999). In this study, no data on other crops were available. Therefore, following the approach of Audsley *et al.* (1997), all the environmental burdens associated with manure and chemical fertilisers were allocated to the production of leek.

Table 2: The different models and data used for the calculation of the nitrogen balance on the conventional and organic farms considered in this study

Nitrogen balance	Conventional farming	Organic farming	Reference
N inputs (total)	**373,88**	**258,88**	
Organic fertilizer application (kg N/ha)	125	235	
initial: cattle manure (kg N/ha)	*125*	*150*	POVLT/PCBT
additional: dried blood and horn meal (kg N/ha)	-	*85*	POVLT/PCBT
Mineral fertilizer application (kg N/ha)	225	-	POVLT/PCBT
Biological fixation	-	-	
Atmospheric N deposition (kg N/ha)	23,88	23,88	Van Gijseghem *et al.*, 2006; van Zeijts and Reus, 1996
N outputs (total)	177,83	117,22	
N removal with harvested crops (kg N/ha)	135	98,34	Vandeberghe *et al.*, 2006
NH_3-N emissions (kg NH_4-N/ha)	7,75	3,90	
due to organic fertilizer application (kg NH_4-N/ha)	*3,25*	*3,90*	Horlacher and Marschner, 1990
due to mineral fertilizer application (kg NH_4-N/ha)	*4,5*	-	ECETOC, 1994
N_2O-N emissions (kg N_2O-N/ha)	4,28	1,83	Bouwman, 1995
N_2-N emissions (kg N_2-N/ha)	30,80	13,15	Brentrup *et al.*, 2000
N balance = $\sum$ input - $\sum$ ouput (kg NO_3-N/ha/year)	**196,05**	**141,66**	Brentrup *et al.*, 2000; 2003

Field emissions related to crop protection

To estimate the amount of pesticides emitted from the field to the different compartments of the surrounding environment the PestLCI model developed by Birkved and Hauschild (2006) was used. PestLCI has been developed in order to overcome the restrictions and data requirements of environmental risk assessment models. PestLCI is capable of predicting the emission fractions of pesticides to air, surface water and ground water to be used in the LCI to calculate emissions which serve as input to the LCIA phase (Birkved and Hauschild, 2006). Since PestLCI is developed for the Danish conditions, the database provided with the model needed to be adapted to the pedological and meteorological conditions typical to the Belgium farming region considered in this study. Besides, the database contains data on active ingredients of 69 pesticides approved in Denmark. However only few of these active ingredients corresponded to those applied in leek production. Therefore, in order to obtain consistent emission data for all pesticides, data on all active ingredients applied in leek farming were inserted in the model, as different data sources may bias the outcome. The emitted fractions to the air and water compartment for the different active ingredients applied are presented in appendix A.

Impact assessment

The life cycle impact assessment phase (LCIA) is the step in which data collected during the LCI are processed and interpreted in terms of environmental impacts (Guinée *et al.*, 2001). The LCIA phase comprises different steps. It is first decided which impact categories will be taken into consideration. In accordance with Guinée *et al.* (2001), the following baseline impact categories are considered in this study: depletion of abiotic resources (ADP), climate change (GWP_{100}), stratospheric ozone depletion (ODP), human toxicity (HTP), terrestrial ecotoxicity (TETP), photochemical oxidant formation (POCP), acidification (AP) and eutrophication (EP).

Next, the indicator result for each impact category is determined. This is done by multiplying the aggregated resources used and the aggregated emissions of each individual substance with a characterisation factor for each impact category to which it may potentially contribute (Heijungs *et al.*, 1992). Characterisation factors (also often referred to as equivalency factors or potentials) are substance-specific, quantitative representations of the additional environmental pressure per unit emission of a substance (Huijbregts *et al.*, 2000). The selected impact categories with their units, main contributing elements and related characterisation factors are presented in table 3.

In the LCA methodology, the impact category 'land use' solely comprises the environmental consequences resulting from occupying, reshaping and managing land for human purposes (Heijungs *et al.*, 1997; Lindeijer, 2000). Direct impacts which are related to land use such as nitrate leaching or diffuse emissions from soil to air are accounted for elsewhere (Brentrup *et al.*, 2003). However, land use by agriculture leads to substantial impacts, particularly on biodiversity and soil quality as a supplier of life support functions. Recently, within the UNEPSETAC Life Cycle Initiative, key elements in a LCIA framework of land use have been treated (Milà i Canals *et al.*, 2007) but today no consensus has been reached yet on a correct methodology to assess the impact of land use (Udo de Haes, 2006). This is the reason why the impact category land use is not considered in this case study.

Several LCIA methods have been developed and published (e.g. CML 1992 (Heijungs *et al.*, 1992a); Eco-Indicator 95 (Goedkoop, 1995); EDIP'97 (Hauschild and Wenzel, 1998); Eco-Indicator 99 (Goedkoop and Spriensma, 1999); CML 2000 (Guinée *et al.*, 2001); IMPACT 2002+ (Jolliet *et al.*, 2003)). This LCIA case study was carried out using the CML 2000 method (Guinée *et al.*, 2001) included in the LCA-software package SimaPro 7.1 (Pre, 2007).

Table 3: Selected impact categories with related units, contributing elements, characterisation factors and models

Impact category	**Unit**	**Contributing elements**	**Characterisation factor**	**Characterisation model description**	**Reference**
Abiotic resource depletion	kg antimony equivalents (kg Sb-equivalents)			Abiotic depletion = $\sum_i ADP_i \times m_i$ ADP_i is the abiotic depletion potential of resource i, while m_i is	Guinée and Heijungs, 1995

				the quantity of resource i used	
Climate change	kg CO_2-equivalents	CO_2 CH_4 N_2O	1 21 310	Climate change = $\sum_i GWP_{100,i} \times m_i$ $GWP_{100,i}$ is the global warming potential for substance i integrated over 100 years, while m_i is the quantity of substance i emitted	Houghton *et al.*, 1994; 1996
Stratospheric ozone depletion	kg trichlorofluoromethane equivalents (kg CFC-11 eq.)	Methyl bromide Tetrachloromethane (CFC-10) CFC-11	0.37 1.2 1	Ozone depletion = $\sum_i ODP_{\infty,i} \times m_i$ $ODP_{\infty,i}$ is the steady-state ozone depletion potential for substance i, while m_i is the quantity of substance i emitted	WMO, 1992; 1999
Human toxicity	kg 1,4-dichlorobenzene equivalent (kg 1,4-DCB eq.)	heavy metals pesticides		Human toxicity = $\sum_i \sum_{ecom} HTP_{ecom,i} \times m_{ecom}$ $HTP_{ecom,i}$ is the human toxicity potential for substance i emitted to emission compartment ecom (=air, fresh water, seawater, agricultural or industrial soil), while $m_{ecom,i}$ is the emission of substance i to medium ecom (calculated with USES-LCA)	Huijbregts, 2000; Huijbregts *et al.*, 2000
Terrestrial ecotoxicity	kg 1,4-dichlorobenzene equivalent (kg 1,4-DCB eq.)	heavy metals pesticides		Terrestrial ecotoxicity = $\sum_i \sum_{ecom} TETP_{ecom,i} \times m_{eco}$ $TETP_{ecom,i}$ is the terrestrial ecotoxicity potential for substance i emitted emission compartment ecom, while $m_{ecom,i}$ is the emission of substance i to medium ecom (calculated with USES-LCA)	Huijbregts, 2000; Huijbregts *et al.*, 2000
Photochemical oxidant formation	kg ethylene equivalents (kg C_2H_2-eq.)	CH_4 aldehydes	0.007 0.443	Oxidant formation = $\sum_i POCP_i \times m_i$ $PCOP_i$ is the photochemical ozone creation potential for substance i, while m_i is the quantity of substance i emitted	Andersson-Sköld *et al.*, 1992
Acidification	kg SO_2-equivalents	NH_3 NO_x	1.6 0.5	Acidification =	Huijbregts, 1999

		SO_2	1.2	$\sum_i AP_i \times m_i$ AP_i is the acidification potential for substance i emitted to air, while m_i is the emission of substance i to the air	
Eutrophication	kg PO_4^{3-} equivalents	NH_3 NH_4^+ NO_3^- NO_x PO_4^{3-} P_2O_5	0.35 0.33 0.1 0.13 1 1.34	Eutrophication = $\sum_i EP_i \times m_i$ EP_i is the eutrophication potential for substance i emitted to air, water or soil, while m_i is the emission of substance i to the air, water or soil	Heijungs *et al.*, 1992

PESTICIDES- The widespread use of pesticides is one of the major impacts of agricultural production. In addition to possible human exposure, pesticide use can also cause ecotoxicological impacts in aquatic and terrestrial systems. Indirect discharges of pesticides may also contribute to decreased biodiversity. Recently, specific methodological improvements have been developed for the assessment of pesticides (Margini *et al.*, 2002) and others need to be devised for heavy metals. The major challenge concerns the capacity of evaluating both types of emission, pesticides and heavy metals simultaneously, and differentiating short- and long-term impacts (Charles *et al.*, 2006).
In order to assess the impact due to the use of pesticides, characterisation factors (i.e. toxicity potentials) had to be calculated since the applied method in SimaPro 7.1 included characterisation factors for only five of the active ingredients applied in leek production, namely thiram, chlorproham, methabenzthiazuron, metazachlor and propachlor. All toxicity potentials were calculated by means of the global nested multi-media fate model USES-LCA (Huijbregts *et al.*, 2000). Within the scope of this study only the impact categories terrestrial ecotoxicity and human toxicity were considered for emissions to the compartments fresh water and agricultural soil (personal communication Huijbregts). In order to obtain consistent characterisation factors for all the active ingredients considered, toxicity potentials for all chemicals were calculated. The calculated characterisation factors are presented in appendix B.

The use of synthetic pesticides is not allowed in organic farming. However, pesticides of natural origin are allowed, such as silicates, copper derivates or extracts of medicinal plants. In leek production, generally only Bacillus thuringiensis (Bt) is used. Due to the lack of physicochemical and toxicity data, no characterisation factors could be calculated for Bt. Since Bt has a low toxicity for the environment, omitting Bt will not significantly influence the outcome. However in other cases – for instance potato or fruit production where a whole range of biological products are used, like copper and sulphur and some insecticides based on pyrethrin – including these biological pesticides is important to allow a more complete comparison of the environmental impact of conventional versus organic agriculture. This has been elucidated for various organic and conventional crops by Vergucht (2007) by evaluating the risks for human health and the environment by means of PRIBEL (Pesticide Risk Indicator for BELgium).

RESULTS

Comparison of impacts of both farming systems per kilogram leek produced

In this section we use a mass-based functional unit (1 kg of leek) indicated further as FU1. When such a mass-based functional unit is considered, organic farming is not always better from environmental point of view. This is shown in Figure 1. The X-axis refers to the different impact categories studied. The values presented on the Y-axis have no dimensions as the figure is meant to present the relative differences between organic and conventional farming. For that, within every impact category, the farming system which causes the lowest environmental impact is compared to the one causing the highest impact. The corresponding indicator results are presented in table 4.

For certain impact categories, conventional farming is favoured due to the fact that the overall yields are usually lower in organic than in conventional systems: with respect to leek production systems considered in this study the yields for organic farming are 27% lower than the yields on the conventional farm. When we compare the resulting impacts, conventional leek production has a 23% lower photo-oxidant formation, a 15% lower ozone depletion, 11% less depletion of abiotic resources, and a 3% lower impact on eutrophication. The conventional production however, shows a substantially higher terrestrial ecotoxicity (100 times higher than for organic farming), human toxicity (about four times higher) and impact on global warming (about two times higher). Related to the acidification potential the impact of organic farming is 15% lower.

Take in Figure 1

Table 4: Compared environmental impact assessment of organic and conventional leek production per kilogram of leek produced

Impact category	**Impact indicator score**			
	Organic leek production		**Conventional leek production**	
Abiotic resource depletion (kg Sb-eq.)	1.75E-4	100 %	1.55E-4	89.09 %
Climate change (kg CO_2-eq.)	4.35E-2	46.08 %	9.44E-2	100 %
Stratospheric ozone depletion (kg CFC-eq.)	3.59E-8	100 %	3.06E-8	85.24 %
Human toxicity (kg 1,4-DB-eq.)	7.48E-3	24.36 %	3.07E-2	100 %
Terrestrial ecotoxicity (kg 1,4-DB-eq.)	3.53E-5	0.51 %	6.91E-3	100 %
Photochemical oxidant formation (kg C_2H_4-eq.)	7.34E-6	100 %	5.66E-6	77.11 %
Acidification (kg SO_2-eq.)	3.82E-4	84.89 %	4.50E-4	100 %
Eutrophication (kg PO_4-eq.)	6.94E-4	100 %	6.74E-4	97.12 %

Abiotic resource depletion

The impact in the category abiotic depletion is mainly due to fossil fuel, energy use and production of mineral fertilizers. As indicated in Appendix C, for on farm activities directly related to the production of leek we calculated a total diesel use of 142,1 l/ha for conventional leek and of 134 l/ha for organic leek. As the average conventional leek yields are 37,5 ton/ha and the average organic leek yields only 27,5 ton/ha, the use of diesel per kg conventional leek (0,0038 l/kg) is 22% lower than for organic leek (0,0049 l/kg). When we also take into account the abiotic depletion related to the production of mineral fertilizers, the result is that conventional farming has an indicator score for abiotic resource depletion that is 11% lower than for organic production per FU1.

Global warming
Table 4 shows that the total climate change indicator score, Global Warming Potential, $GWP_{100,}$ is 0.094 kg CO_2-equivalents/kg leek for the conventional system and 0.044 kg CO_2-equivalents/kg leek for the organic system, revealing conventional leek production to have a substantially higher impact on climate change. The GWP depends mainly on the use of fossil fuels for on farm activities, energy use for the production of inputs and emissions of N_2O connected to the on-farm nitrogen cycle. As indicated above the use of diesel per kg conventional leek is 22% lower than for organic leek. However, the use of fossil fuel is not the only contributing factor. Emissions of N_2O connected to the on-farm nitrogen cycle and synthetic fertilizers production have a larger share than CO_2-emissions from fossil fuel use, eventually resulting in a higher impact score per FU1 for the conventional system since these emissions are higher per kg of conventional leek.

Stratospheric ozone depletion
Compounds such as methane, nitrous oxide and carbon monoxide can directly or indirectly influence stratospheric ozone depletion (Cederberg and Mattson, 2000). It has been estimated that doubling the concentration of nitrous oxide in the atmosphere would result in a 10% decrease in the ozone layer, increasing the ultraviolet radiation reaching the earth by 20% (Mosier *et al.*, 1998). As the pollutant inventory does not contain substances which substantially contribute to this category (e.g. CFC, HCFC or halon-emissions) the indicator score for this category is very low for both organic ($3.59*10^{-8}$ kg CFC eq.) and conventional farming systems ($3.06*10^{-8}$ kg CFC-eq). Therefore, we agree with Audsley *et al.* (1997), Van Dijk (2001), Berlin (2002), de Boer (2003) and Hospido *et al.* (2003) that ozone depletion may be left out of consideration when discussing farming systems, seen its negligible impact.

Human toxicity and terrestrial ecotoxicity
Human exposure to toxic substance, through air, water, soil or the food chain, can cause serious health problems. A toxicity assessment in agriculture mainly focuses on the effect of the exposure to pesticides and heavy metals on humans and ecosystems (de Boer, 2003). Since no exact figures on the heavy metal emission were available these were not included in the analysis. The pesticide use in conventional farming systems nearly completely determines the human toxicity impact score. In organic farming the use of synthetic pesticides is banned consequently resulting in a much lower total indicator score of 0.0075 kg 1,4 DB-equivalents/kg organic leek compared to 0.031 kg 1,4 DB-equivalents/kg conventional leek. The potential human toxic effect of organic leek production mainly results from the potential toxic effect due to the emissions released during fuel combustion processes. The same applies for the category terrestrial ecotoxicity with this distinction that the potential ecotoxic effect resulting from energy use is considerably lower, consequently further increasing the difference between the organic and conventional system.

Photo-oxidant formation
Reactions of NO_x with volatile organic substances, under the influence of UV light, lead to photochemical oxidant creation, which causes smog. Due to the higher use of tractor diesel fuel per FU1 on the organic farm studied, the emission of NO_x, catalyst of the photo-oxidant reaction, is greater. The higher amount of diesel consumed per FU1 also results in a larger emission of CO and hydrocarbons, consequently resulting in a higher impact score for the organic system.

Acidification

The emission of NH_3, N_2O, NO_x, SO_2 and SO_x into the air and their subsequent combination with other molecules results in acidification of ecosystems. Ammonia is the key parameter affecting the impact indicator score for farming systems. On-farm ammonia mainly volatilizes during application of manure and artificial fertilizers. Table 2 showed the amount of NH_3 emitted by the conventional leek production to be considerably higher than the amount emitted by the organic system, thus leading to an indicator result of 0.00045 kg SO_2-equivalents/kg leek, which is 18% higher than for the organic system (0.00038 kg SO_2-equivalents/kg leek).

Eutrophication

Eutrophication is the emission of nutrients, mainly via water but also to the air, which thereby find there way to other ecosystems and affect their relative growth patterns posing a threat to biodiversity. The eutrophication impact category accounts for both nitrogen and phosphorus emissions. On-farm eutrophication mainly comprises leaching of nitrate and phosphate, and volatilisation of ammonia during fertilizer application. The indicator result for the conventional system is slightly lower (2.9%) than the one for the organic production. This is mainly due to the higher yields per ha for conventional leek production. It is partly due to the fact that in organic systems more P-run-off occurs (0.89 kg P/ha) compared to the conventional system (0.74 kg P/ha), because of higher quantities of manure applied in the organic system. In conventional systems synthetic mineral fertilizers are often used, which are not allowed in organic farming systems.

Comparison of impacts of both farming systems per square metre leek production

The environmental profile obtained when the FU is taken to be one square metre of leek production is presented in figure 2. The corresponding impact indicator scores are listed in table 5. For all relevant impact categories considered, the impact of one square metre of organically grown leek is lower than the impact caused by its conventional equivalent. The use of pesticides in conventional production systems considerably contributes to the impact categories human toxicity and terrestrial ecotoxicity. The higher emissions of nitrogen per square metre due the application of mineral fertilizers result in a higher impact score for the categories eutrophication and acidification. Furthermore, the lower energy requirements in the organic system result in a substantially lower impact on abiotic resource depletion, global warming, ozone depletion and photo-oxidant formation.

Take in Figure 2

Table 5: Compared environmental impact assessment of organic and conventional leek production per square metre of leek produced

Impact category	**Impact indicator score**			
	Organic leek production		**Conventional leek production**	
Abiotic resource depletion (kg Sb-eq.)	4.81E-4	82.22 %	5.85E-4	100 %
Climate change (kg CO_2-eq.)	1.20E-1	33.61 %	3.57E-1	100 %
Stratospheric ozone depletion (kg CFC-eq.)	9.88E-8	85.17%	1.16E-7	100 %
Human toxicity (kg 1,4-DB-eq.)	2.06E-2	17.76%	1.16E-1	100 %
Terrestrial ecotoxicity (kg 1,4-DB-eq.)	9.71E-5	0.37 %	2.60E-2	100 %
Photochemical oxidant formation (kg C_2H_4-eq.)	2.02E-5	94.84 %	2.13E-5	100 %
Acidification (kg SO_2-eq.)	1.05E-3	61.76 %	1.70E-3	100 %
Eutrophication (kg PO_4-eq.)	1.91E-3	75.20 %	2.54E-3	100 %

Impact of the different farming activities for conventional leek production

Figure 3 gives an overview of the contribution of the different farming activities as a share of the total impact for conventional leek production, and this for each of the environmental impact categories discussed in this paper. On the X-axis, the different impact categories are presented. For each category the overall impact score, which is shown on the Y-axis, is attributed a total score of 100%.

Take in figure 3

One can notice that fertilising and applying crop protection products are to a great extent responsible for the overall environmental impact of conventional leek production. Fertilization processes account for 98% of total impact on eutrophication, for 87% on Global Warming potential and for 83% of acidification. The large impact of the fertilization process within the impact category global warming is mainly due to the way this process is defined within SimaPro. The fertilization process consists of applying both mineral and organic fertilizers, and in case of organic fertilizer working the latter into the soil. This process thus involves a lot of diesel emission, subsequently resulting in a lot of greenhouse gas emissions when compared to other processes. Also emissions resulting from the production of ammonium nitrate and transporting the manure from the livestock breeding farm to the leek production farm contribute to the emission of greenhouse gasses.

The same applies for the formation of photochemical oxidants (namely comprising the emissions of NOx and VOS). The application of fertilizers is responsible for almost the entire impact within the category eutrophication, mainly as a result of the emissions of the eutrophying components nitrate (NO3), ammonia (NH3) dinitrogen monoxide (N2O), nitrogen oxides (NOX), and phosphorus (P). The emissions of NOx and NH3 are the chief contributors to the high score within the impact category acidification.

Applying crop protection products is responsible for 85% of the impact on human toxicity and completely (100%) for the impact on terrestrial ecotoxicity.

Impact of the different farming activities for organic leek production

Figure 4 presents the contribution of the different farming activities involved in the production of organic leek as a share of the total impact for the environmental impact categories discussed. In the case of organic leek production, “fertilizing” is the process which has the strongest impact on all impact categories studied, varying from a share of 51% for the indicator “ozone layer depletion” up to a share 97% for the indicator “eutrophication”.

Take in figure 4

The important share of “fertilization” on the different environmental impact indicators is due to the fact that it comprises a number of different subactivities (e.g. loading, applying and working it into the soil) each involving the emission of greenhouses gases resulting from the usage of diesel. The emission of the eutrophying compounds like nitrate (NO3), ammonia (NH3), dinitrogen monoxide (N2O), nitrogen oxides (NOx) and phosphorus (P) mainly affect the overall impact score for the impact category eutrophication. The emission of NOx and NH3 chiefly determine the score within the impact category acidification.

DISCUSSION

The choice of the functional unit

As illustrated above in our analysis, the impact assessment is largely dependent on the choice of the FU, which should be related to the main functions assigned to the farming system and the objectives of the evaluation.

Berlin and Uhlin (2004) and Grönroos *et al.* (2001) argue that land use should be considered as the basis for the functional unit for agricultural products because this would facilitate policy decisions regarding land use and regional planning. Area of land used reflects an effort to incorporate non-market goods such as environmental services in the LCA framework, and raises interesting questions regarding the influence of land use practices on the outcome of such an assessment (Schau and Fet, 2008). Basing the functional unit on land use, however, precludes the inclusion of the land use impact category which would complicate LCAs where the entire value chain, not only agriculture, is included.

Brentrup (2003) suggests using a product-related functional unit (i.e. based on mass) rather than an area-related functional unit in order to be capable of assessing differences in land use efficiency. An LCA where the functional unit is based on land use will bring the LCA method closer to the Environmental Impact Assessment process, aims of which are, among other, to assess location choices (Tukker, 2000). This shows that the choice of the functional unit is highly dependent on the aim of the study. For example, in studies intended to advise consumers regarding food products (Jungbluth *et al.*, 2000), mass, volume or nutrient contents may be more relevant than land use as a basis for the functional unit.

Since no consensus has been reached on this topic, several LCA practitioners cope with this methodological issue by defining multiple FUs each highlighting another function of the farming system (e.g. Basset-Mens and van der Werf, 2005; Charles *et al.*, 2006; Mouron *et al.*, 2006). As stated by Charles *et al.* (2006) and van der Werf *et al.* (2007), we strongly recommend to consider both the assessment per unit area and per unit of production, respecting the multi-functionality of agriculture. When the FU is per kg production both the production efficiency and the environmental impact are considered. When the focus is on the environmental impact in a local area, the FU per area production, is more appropriate. The influence of the choice of FU is very important when comparing systems with different levels of productivity per ha, such as conventional and organic farming (Basset-Mens and van der Werf, 2005).

More efficient recycling and whole-farm nitrogen balances

Emission of the nitrogen pollutants ammonia and nitrate are major sources for eutrophication and acidification, being hot-spots in both systems studied. Ammonia, being an acidifying as well as a nutrifying compound is closely connected to the handling of farmyard manure and inorganic fertilizers. Adequate measures relying on more efficient recycling and greater retention of nitrogen in the system (e.g. changes in cropping patterns, more use of catch crops in autumn and winter) should be assessed in terms of whole-farm nitrogen balances. When expressed on area basis, the organic system has a lower eutrophication potential. This is in line with the organic philosophy as organic farming aims to minimise nutrient losses.

Reducing the use of pesticides

This study shows that when assessed on area basis organic farming shows a more favourable environmental profile, most apparent being the absence in use of synthetic pesticides. This is strongly reflected by the good indicator scores for human toxicity and ecotoxicity. Even though the outcome is strongly affected by the FU applied, these benefits clearly show under both definitions, i.e. per unit of product and per area. Consequently, one of the most important improvement possibilities for conventional systems concerns the reduced use of pesticides. A shift towards more disease resistant cultivars and the use of crop monitoring systems to determine the most appropriate window of application could substantially decrease its dependency on pesticides without losing too much yield, the latter being one of the major bottlenecks of organic farming as the use of synthetic pesticides is not allowed in organic systems. However, certain mineral compounds are approved for use in crop protection on the basis that they are not synthetic. Supplementary nutrients in the form of mineral and organic fertilizers also form an important part of organic crop protection programmes as these additional nutrients promote mechanical resistance in the plant cells and reduce the susceptibility of plants to attack (Edwards-Jones and Howells, 2001). To date, not much is known about the impact of natural pesticides (van Zeijts *et al.*, 2003). More research work is needed to assess the possible impacts of the use of natural pesticides and to implement them in LCA. Stolze *et al.* (2000) conclude that organic farming is by far superior as compared to conventional farming. Others are more reserved, suggesting that the compounds are not without toxicological hazards to ecology or humans (Edwards-Jones and Howells, 2001). Leake (1999) states that some natural chemicals are more toxic and persistent than their synthetic equivalent, e.g. the toxicity for bees of the natural pesticide pyrethrin is higher than the toxicity of the synthetic equivalents lambda-cyhalothrin and deltamethrin. Generally, pesticides and fungicides permitted for use in organic farms are less hazardous than those used in conventional systems, but there are some clear exceptions to this rule. However, some evidence suggests that when toxicity and volume are considered in an overall pest management strategy, organic pesticides may constitute a greater environmental hazard than conventional ones (Kovach *et al.*, 1992; Edwards-Jones and Howells, 2001), due to higher number of applications required. Moreover, natural pesticides such as sulphur and copper sulphate have a relevant impact during their production (Nicoletti *et al.*, 2001), requiring these upstream emissions to be considered as well. Overall it can be concluded that organic farms cause a lower environmental burden by pesticide usage than conventional farming (van Zeijts *et al.*, 2003).

In integrated crop management (ICM) use of pesticides is minimized. In most ICM systems total active ingredient input is less than half of the amount used in conventional farming. In some cases the total input has been reduced by more than 90% (van Zeijts *et al.*, 2003). Integrating or evolving towards such production strategies might be a reasonable improvement means for conventional farming.

Increasing efficiency

Other LCA studies (e.g. Geier and Kopker, 1998; Haas *et al.*, 2001) have also clearly shown that organic farming has ecological advantages compared to conventional farming when measured per unit of area. However, a recent meta-analysis from Mondelaers et al. (2009) based upon the general results of 10 studies of organic farming in developed countries, finds that yields on organic farms are on average 17% lower than on conventional farms, ceteris paribus. So after taking into account these lower yields another environmental profile is obtained. Specifically for leek production in Belgium we mentioned already that the average yields are 27 % lower in organic farming than on conventionally cultivated fields. Environmental problems in arable systems are often reduced to nitrogen and pesticides problems, which ignores the specific high efficiency associated with these inputs to the whole agricultural production system.

Mattson and Wallén (2003) showed in a case study on organic potatoes that devising measures for pest control is an important improvement option as the limited means for controlling pests are responsible for the low yields. Raising the yields as important improvement measure for organic systems was also stated by Cederberg and Mattson (2000) and Cederberg and Flysjö (2004) (dairy farming), Nicoletti *et al.* (2001) (viticulture), and Kramer *et al.* (2000), van Woerden (2001) and Halberg (2006) (horticulture and greenhouse farming) in their comparative studies. Gaillard and Nemecek (2002) and Charles *et al.* (2006) demonstrated that low input wheat production systems are more favourable only if a sufficient yield level is obtained and Brentrup *et al.* (2004) concluded that a good environmental performance was achieved in wheat production systems by maintaining high-yields in order to use land most efficiently, to apply fertilizers to crop demand and to limit emissions of NO_3, NH_3 and N_2O.

Communications to consumers

A recent study from Tobler et al. (2009) indicate that there exists still an important gap between the perception of consumers and experts about the negative environmental impact of vegetable production, transport, conservation and packaging. Especially the difference in negative impact from air transport in comparison with truck transport, seems to be underestimated by consumers. Consumers seem to strongly overestimate the negative impact of conservation and especially packaging. It therefore seems important that consumers would be better informed.

Limitations and suggestions for future research

The LCA is based on what we believe to be accurate information provided by the two research centra mentioned earlier. The data provided are average production data and or not based on data collection for a single year. The data represent common types of production for both conventional and organic leek. A limitation of this paper is that the study is limited to the case of leek production. A comparison between organic and conventional production for other types of production may result in different findings. It would be interesting if future research would apply the methodology to other crops. Jungbluth et al. (2000) have found that in comparison to the production of organic vegetables, the impact of the production of organic meat is about 10 times larger, expressed in UBP/kg (UmweltBelastingsPunkte).

As indicated our LCA is limited from cradle to farm-gate. Future research can be expanded to comprise all phases from cradle-to-grave to get a better idea of the total sustainability of our present food consumption patterns. From the farm-gate on, processes that then will have to be considered are distribution (transport, especially air-transport), processing and conservation (e.g. deep freezing) and to a minor extent packaging. An important impact on the environment is expected from the transport and use of fuel. In that case especially the transport distance and transport efficiency will matter. In the case of leek production in Flanders we get signals from the market that transport efficiency for organic vegetables are probably lower, mainly due to the lower volumes that are transported, resulting in lorries that are not always full. Also average travel distances are expected to be longer for organic vegetables in Flanders as the there are fewer distribution centres than for conventional vegetables. However these are assumptions that have to be checked by future research. Important however for the European organic sector in general is that important quantities are imported from oversees. Padel et al. (2008) report that on average (only) 66 percent of the organic primary produce sold by multiple retailers in the UK were sourced from the UK in 2006 and that with demands outpacing supply imports are likely to increase. Jungbluth et al. (2000) have found that in a full LCA of vegetables by far the strongest negative impact results from air transport. Also production in greenhouses and deep freezing has an imortant negative impact.

Comparing different systems producing similar products also requires a high degree of accuracy for inventory data (Basset-Mens and van der Werf, 2005; Thomassen *et al.*, 2008). This study does not consider the complete crop rotation and organic matter content of the soil, consequently not considering an important feature of organic farming. Organic farming systems which involve the use of catch crops, the recycling of crop residues, the use of organic rather than artificial fertilisers, and the use of perennial crops are assumed to promote higher levels of organic matter in the soil (Stolze *et al.,* 2000), although appropriate research is needed to confirm this (Hansen *et al.*, 2001). Taking these methodological constraints into account, the major environmental hot-spots of both systems studied have been identified and compared.

CONCLUSION

In order to assess the full environmental impacts of agriculture, off-site effects should also be taken into account. The importance of addressing these indirect impacts is obvious in the need to move towards a more sustainable food production system. The desire for sustainable agriculture is universal, yet agreement on how to progress towards it still remains elusive. In this respect, life cycle assessment is a valuable tool to address questions on the total environmental impact of various agriculture production systems as it assesses and evaluates all relevant impacts simultaneously, however, the outcome is strongly influenced by the system boundaries definition, the choice of functional unit and the impact categories considered.

This study shows that when assessed on area basis organic farming shows a more favourable environmental profile. Suggested improvements for conventional farming are improving the farm nutrient flows in order to reduce nutrient surplus, optimizing the energy and fuel use, increasing its self-supporting capacity and reducing the use of toxic pesticides. Since the yields obtained by organic farming are lower compared with conventional farming, the overall environmental benefits are strongly reduced or even disappear after correcting for these lower produced quantities per hectare. Therefore, more research should be done on how the yields in organic farming can be substantially increased without increasing the environmental burden.
These findings imply that there is no ‘right’ choice open to objectification, as the outcome is strongly affected by the initial choices made. When emphasis is put on efficiency, conventional farming performs better. When focus is on the impact per area of land, organic farming is clearly preferable to conventional farming. Improving the yields in organic farming can substantially render the choice in favour of the latter. However, it might be interesting to broaden the view and consider the fact that organic farming might not be the only solution for sustainable agriculture. Evolving to a more integrated farming approach achieving yields that fall mid-way between the high yields of conventional agriculture and the lower yields under organic systems, still relying on the use of inorganic inputs, albeit at lower levels than those of conventional systems, sustaining sufficient agricultural production and safeguarding the environment may give a fair answer to the sustainability issue.

This study only highlights the ecological aspect of sustainability. To get an overall picture of the sustainability of organic and conventional farming, social and economical aspects should also be taken into consideration.

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Appendix A: Emitted amount of pesticide active ingredients resulting from field application and assessed by means of the PestLCI model adapted to the Belgian case*

Active ingredient	Application dose (g/ha)	Time of application	Emitted amount of active ingredient (g)	
			Air	Water
Seedbed				
metam-sodium***	7500	01/09	-	-
Thiram	0,86	-	1.01E-01	3.28E-05
propachlor	54	30/03	8.78E+00	2.26E-03
chlorpropham	15	30/03	5.41E+00	5.15E-02
Pyridate	17	15/04	1.84E+00	2.45E-04
methiocarb	19	23/06	2.06E+00	1.84E+00
Arable field				
abamectin	9	15/07	2.28E+00	3.35E-92
azoxystrobin	250	01/09	9.95E+01	6.10E+00
	250	15/09	9.95E+01	6.10E+00
	250	15/10	1.48E+02	4.09E+00
boscalid***	400	15/07	-	-
	400	01/11	-	-
cyproconazole	60	01/09	2.39E+01	1.07E+00
haloxyfop-R-methyl	108	15/07	2.74E+01	7.22E-02
	108	15/08	2.74E+01	7.27E-02
lambda cyhalothrin	5	01/08	1.27E+00	1.56E-01
mancozeb	2800	01/07	3.02E+02	2.49E+00
	1600	15/08	4.05E+02	1.19E+00
	2800	01/10	1.66E+03	1.19E+00
	400	01/11	2.37E+02	1.72E-01
metazachlor	600	08/06	6.52E+01	3.55E-02
methabenzthiazuron	700	08/06	7.58E+01	4.24E+01
methiocarb	750	01/07	8.14E+01	7.26E+01
	750	01/08	1.90E+02	6.06E+01
	750	01/09	2.99E+02	4.89E+01
	750	01/10	4.44E+02	3.27E+01
pyraclostrobin***	100	15/07	-	-
	100	01/11	-	-
Pyridate	900	15/06	9.72E+01	2.18E-03
spinosad***	96	15/06	-	-
	96	15/08	-	-
tebuconazole	250	01/07	2.70E+01	2.97E+01
	250	15/08	6.33E+01	2.47E+01
	250	01/10	1.48E+02	1.33E+01
thiophanate-methyl***	2500	25/	-	-

* The data needed for adapting the Danish model to the Belgian case study were retrieved from the following sources: European Union (http://ec.europa.eu/food/plant/protection/evaluation/index_en.htm); CTB – The Netherlands (http://www.ctb-wageningen.nl/); Pandora's Box (Linders *et al.*, 1994); The Pesticide Manual (Tomlin, 2003); Extoxnet (http://extoxnet.orst.edu/) and Toxnet (http://toxnet.nlm.nih.gov/).

** as emission to soil always occurs indirectly via the air compartment (only theoretically possible via water), e.g. via drift, the fractions emitted to the soil are put to zero (pers. comm. Birkved)

*** due to a lack of physicochemical and toxicological data no emitted masses were assessed for metam-natrium, boscalid, pyraclostrobin, spinosad and thiophanate-methyl

Appendix B: **Toxicity potentials of the pesticides used in conventional leek production related to the emission compartments air, fresh water and agricultural soil, and the impact categories terrestrial ecotoxicity (TETP) and human toxicity (HTP) assessed by means of USES-LCA**

Active ingredient		Type	Initial emission compartment		
Name	Cas number(**)		Air	Fresh water	Agricultural soil
metam-sodium	137-42-8	TETP	6.10E-02	3.00E+07	1.30E-01
		HTP	1.10E-06	2.50E-12	6.90E-16
Pyridate	55512-33-9	TETP	2.90E+00	1.40E-06	4.20E+00
		HTP	1.10E-03	5.30E-10	3.40E-08
methiocarb	2032-65-7	TETP	2.00E+02	1.30E-03	2.70E+02
		HTP	4.50E-03	2.90E-08	2.30E-07
thiophanate-methyl	23564-05-8	TETP	2.40E+02	7.90E+00	1.20E-01
		HTP	1.60E-03	7.80E-04	3.00E+07
spinosad*	168316-95-8	TETP	-	-	-
		HTP	3.60E-03	5.10E-10	8.70E-09
mancozeb	8018-01-7	TETP	2.30E+00	5.10E-08	4.00E+00
		HTP	4.20E-03	9.20E-11	9.00E-10
tebuconazole	107534-96-3	TETP	5.30E+00	2.10E-02	1.10E+00
		HTP	3.50E-03	5.20E-05	3.10E-07
abamectin	71751-41-2	TETP	6.00E+02	6.00E-01	8.60E-01
		HTP	7.40E+02	4.30E+03	2.20E+00
haloxyfop-R-methyl	72619-32-0	TETP	1.80E+01	1.90E-02	3.40E-03
		HTP	1.20E+00	2.10E-02	8.80E-06
pyraclostrobin	175013-18-0	TETP	2.20E+03	1.70E-02	1.20E+00
		HTP	1.40E-01	1.50E-05	2.10E-08
boscalid*	188425-85-6	TETP	-	-	-
		HTP	9.00E+03	1.30E+04	8.40E+02
lambda-cyhalothrin	91465-08-6	TETP	4.00E+00	1.00E-01	1.50E+01
		HTP	4.30E-01	1.10E-02	3.40E-06
cyproconazole	94361-06-5	TETP	6.50E+00	1.40E-04	6.90E+00
		HTP	2.50E-03	5.40E-08	4.90E-07
azoxystrobin	131860-33-8	TETP	3.20E+01	4.60E-05	1.00E+00
		HTP	2.60E+03	5.20E+02	2.20E+01
metazachlor	67129-08-2	TETP	1.00E+00	2.70E-05	1.10E+00
		HTP	1.10E-03	3.00E-08	4.70E-08
methabenzthiazuron	18691-97-9	TETP	4.80E+02	3.00E-02	8.20E+02
		HTP	8.90E-04	5.50E-08	1.60E-07
propachlor	1918-16-7	TETP	4.70E-01	3.40E-03	1.30E+00
		HTP	3.90E-02	2.80E-04	3.00E-05

* no TETPs were calculated for spinosad and boscalid due to a lack of physicochemical and toxicological data

** Cas number = CAS numbers are unique numerical identifiers for chemical substances, elements or compounds. The Chemical Abstracts Service (CAS), a division of the American Chemical Society, assigns these identifiers to every chemical that has been described in the literature in order to facilitate database searches as chemicals often have various different names.

Appendix C: Mechanical operations and consumption of Diesel (L/ha) for conventional and organic leek production (L/ha) (KTBL, 2005)

Operation	**Diesel use (L/ha)***	**Conventional**		**Organic**	
		Number of operations	**Total (L/ha)**	**Number of operations**	**Total (L/ha)**
Working green manure into soil (rotary cultivator)	7,5	1	7,5	1	7,5
Soil cultivation	4,6	1	4,6	1	4,6
Fertilisation – organic					
Loading	3,1	1	3,1	1	3,1
Spreading	11,6	1	11,6	1	11,6
Fertilisation – anorganic					
Loading	0,1	2	0,2	1	0,1**
Spreading	0,8	2	1,6	1	0,8**
Working manure into the soil	7,1	1	7,1	1	7,1
Applying lime	1,8	1	1,8	1	1,8
Ploughing	16,4	1	16,4	1	16,4
Rotary harrowing	7,7	1	7,7	1	7,7
Planting	17,8	1	17,8	1	17,8
Weeding and earthing up	3,1	2	6,2	5	15,5
Spraying	1,5	11	16,5	-	-
Harvesting	40	1	40	1	40
Total:			**142,1**		**134,0**

* all data are from KTBL-report (2005) for average farms with parcels with average size of 2ha on sand loam soil
** Spreading these organic fertilisers (e.g. blood meal) consumes an equal amount of diesel as the mineral fertiliser

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Figure 1: Comparison of the impact of 1 kg of organic and conventional leek production

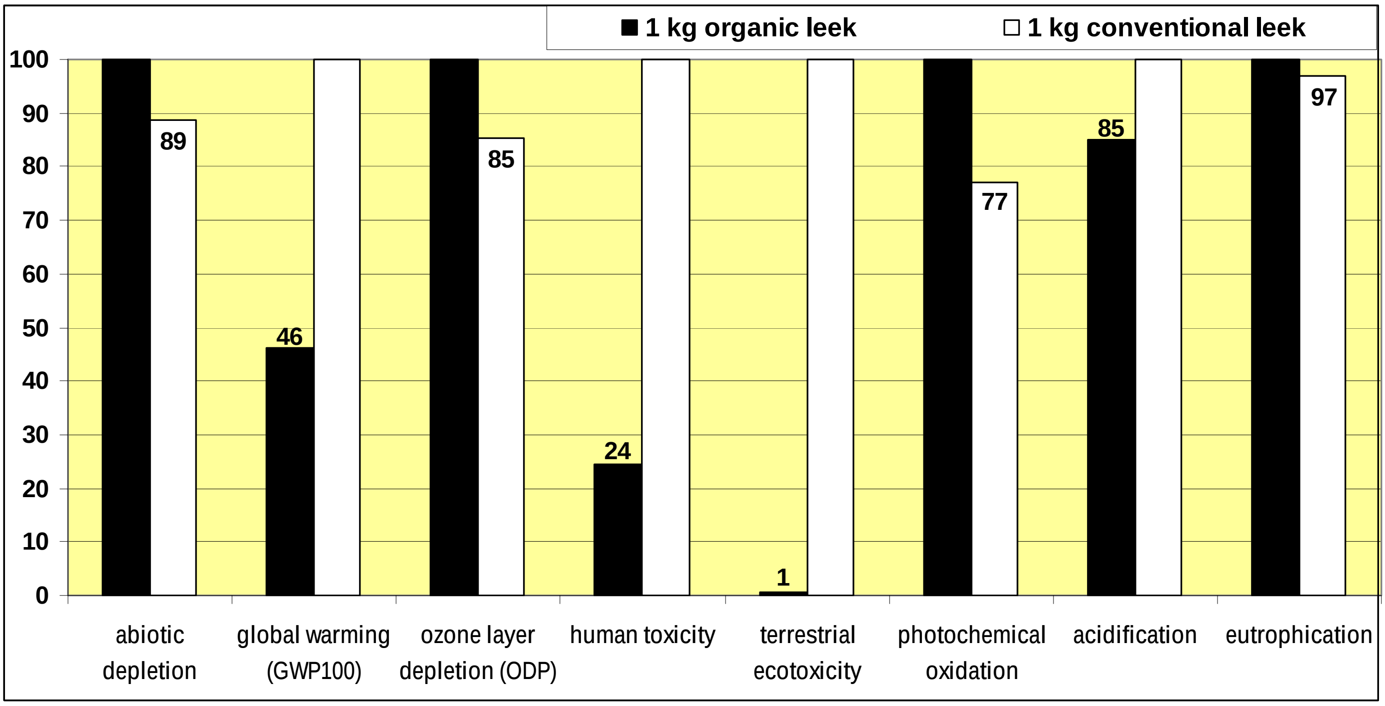

Figure 2: Comparison of the impact of 1 m² of organic and conventional leek production

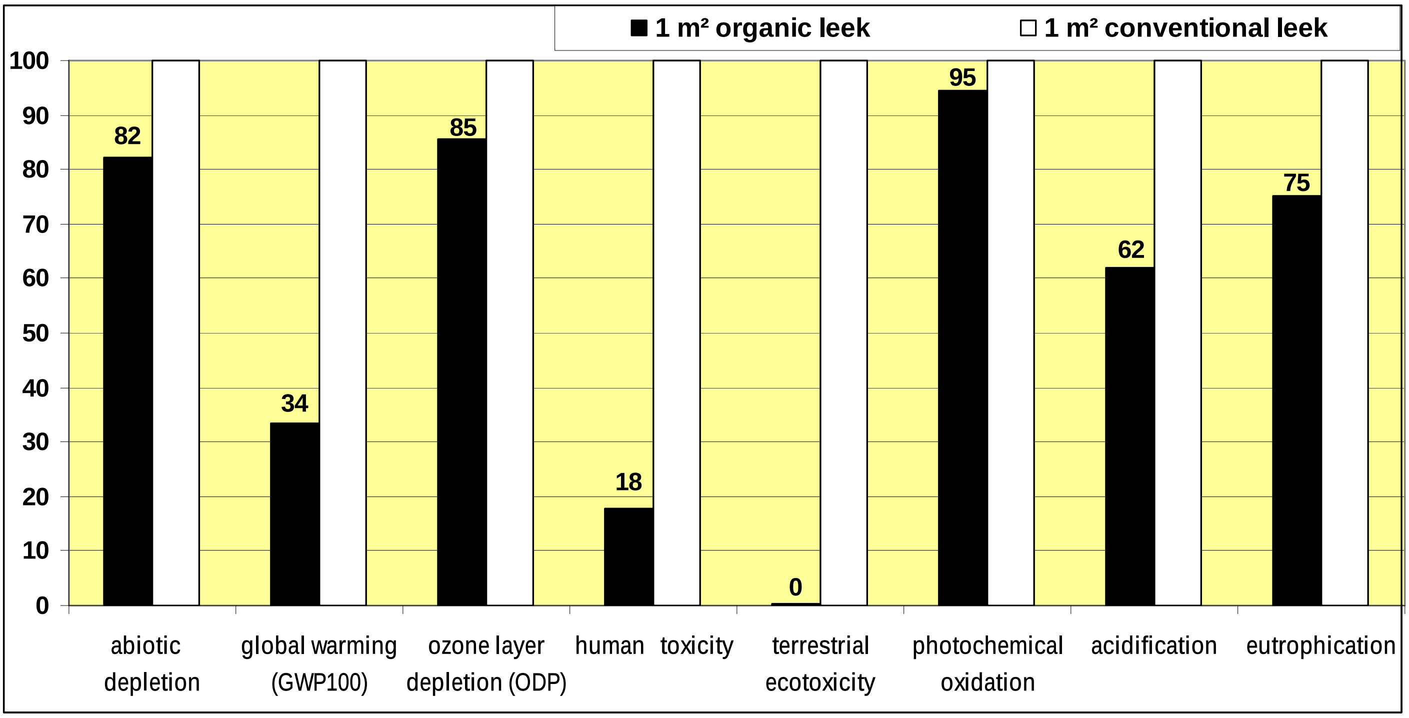

Figure 3: Contribution of farming activities (in %) to the environmental impact indicators, for the production of conventional leek.

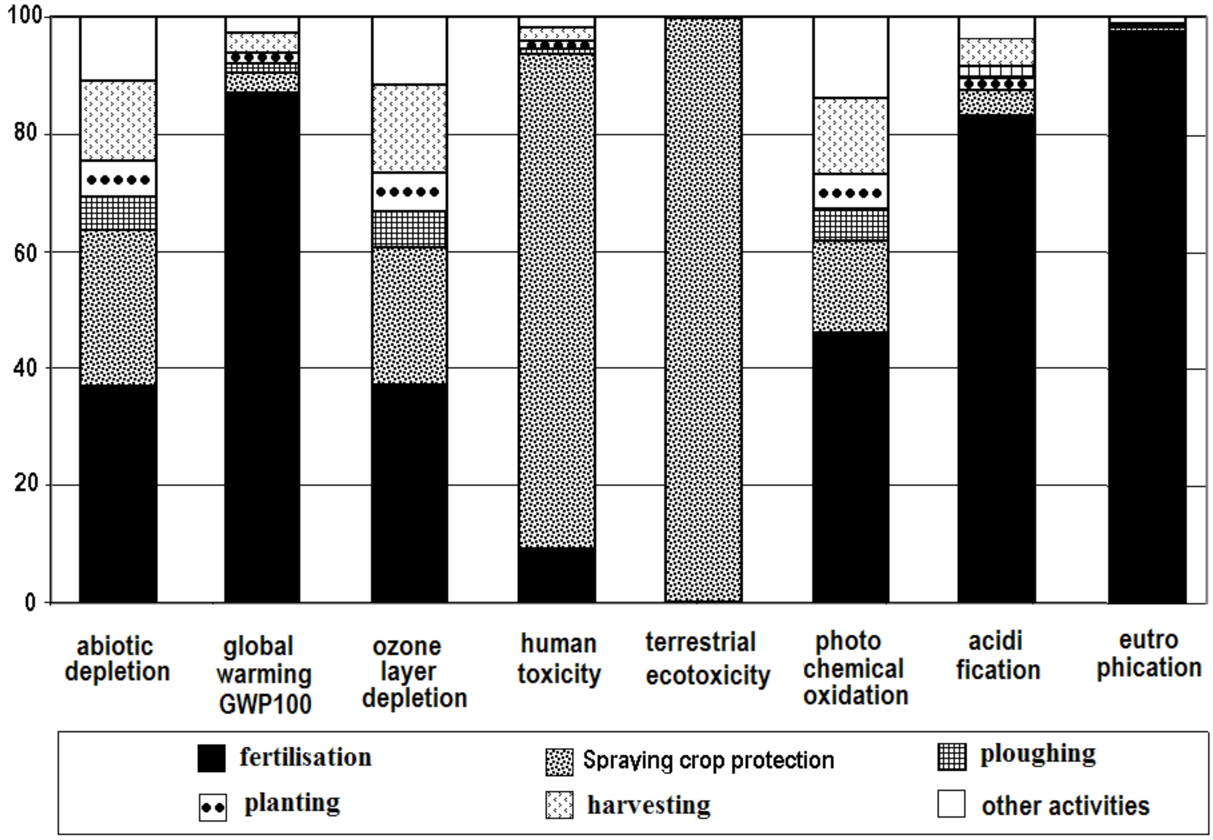

Figure 4: Contribution of farming activities (in %) to the environmental impact indicators, for the production of organic leek.